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The importance of use and end-of-life phases to the life cycle greenhouse gas (GHG) emissions of concrete – A review

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ABSTRACT

Global climate change is one of the most significant environmental impacts at the moment. One central issue for the building and construction industry to address global climate change is the development of credible carbon labelling schemes for building materials. Various carbon labelling schemes have been developed for concrete due to its high contribution to global greenhouse gas (GHG) emissions. However, as most carbon labelling schemes adopt cradle-to-gate as system boundary, the credibility of the eco-label information may not be satisfactory because recent studies show that the use and end-of-life phases can have a significant impact on the life cycle GHG emissions of concrete in terms of carbonation, maintenance and rehabilitation, other indirect emissions, and recycling activities. A comprehensive review on the life cycle assessment of concrete is presented to holistically examine the importance of use and end-of-life phases to the life cycle GHG quantification of concrete. The recent published *ISO 14067*: *Carbon footprint of products – requirements and guidelines for quantification and communication* also mandates the use of cradle-to-grave to provide publicly available eco-label information when the use and end-of-life phases of concrete can be appropriately simulated. With the support of Building Information Modelling (BIM) and other simulation technologies, the contribution of use and end-of-life phases to the life cycle GHG emissions of concrete should not be overlooked in future studies.

Contents

1. Introduction

Climate change has emerged as one of the most pressing environmental issues in recent years. It can cause big threats to future development, including raising sea level and causing natural disasters. According to the IPCC [25], 11 of the last 12 years (1995–2006) ranked among the 12 warmest years in the instrumental record of global surface temperature since 1850. Global average sea level has risen since 1960 at an average rate of 1.8 mm/year and since 1993 at 3.1 mm/year, which has a considerable impact on future development [25]. Billions of people are exposed to natural disaster risks, including weather-related

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disasters that take lives, damage infrastructure and natural resources, and disrupt economic activities [52]. If actions were not taken to reduce greenhouse gas (GHG) emissions, the overall costs and risks of climate change would be equivalent to losing at least 5% of global GDP per year, now and forever [61].

The building and construction industry contributes to the increase of carbon emissions level in many aspects, such as manufacturing of raw materials and transportation of finished products. The cement section alone accounts for 5% of global man-made CO_2 emissions [72]. Manufacturing of raw materials (e.g. cement and steel) and chemicals have considerable impact on CO_2 emissions [73]. Transportation of raw construction materials is also energy intensive, especially for countries like Singapore which heavily relies on the import of raw materials [75]. Additionally, on-site construction of building is not always effective and may generate unnecessary carbon emissions [76]. As one of the largest sources of emissions, the building and construction industry is facing increasing pressure to reduce greenhouse gas (GHG) emissions.

One central issue in striving towards reduced GHG emissions is the need for a practicable and meaningful yardstick for assessing and communicating GHG results [11]. Thus, a number of carbon labelling schemes have been initiated globally, e.g. the Singapore Green Labelling Scheme (Singapore), the Hong Kong Carbon Labelling Scheme (Hong Kong), the CarbonFree (U.S.), the CO_2 Measured Label (UK) and the CarbonCounted (Canada). In these carbon labelling schemes, life cycle assessment (LCA) approaches were adopted to quantify GHG emissions. However, although LCA is adopted as the quantification method, a significant number of carbon labelling schemes choose cradle-to-gate as system boundary, claiming that the GHG emissions and removals in the use and end-of-life stages are insignificant and therefore can be neglected (e.g. [9,17]).

There was a considerable debate over the treatment of emissions generated from the use and end-of-life phases of products and whether the treatment should be included or excluded [57]. The main reason for excluding use and end-of-life phases is the large number of uncertainties regarding how products/materials will be used due to varied user behaviours in terms of activities such as maintenance, replacements, recycling and reuse. However, carbon footprint of the products (CFPs) (i.e. the carbon label) will not be complete to support informed decisions when use phase and end-of-life phase may have a significant impact on the life cycle GHG emissions. This paper therefore aims to examine the importance of use and end-of-life phases to the life cycle GHG emissions of concrete based on the high contribution of cement and concrete to global GHG emissions. It is believed that the findings of this study will help improve current carbon labelling schemes for construction materials, especially concrete, by including use and end-of-life phases. This will allow customers to make informed decisions by providing credible environmental information.

2. The life cycle assessment of concrete

According to the United Nations Environment Programme [66], the life cycle of building materials can be divided into five phases, from extraction of raw materials to demolition. The first phase is related to the extraction and production of building materials, which is also known as cradle-to-gate that includes life cycle stages from the extraction or acquisition of raw materials to the point at which the product leaves the organization undertaking the assessment [4, p. 2]. GHG emitted during this phase is known as embodied carbon. The second and third phases correspond to the transport of building materials from production factories to construction sites, as well as the building construction. The fourth phase is the use of building materials through its service life. Finally, the fifth phase is related to end-of-life treatments of building materials. A cradle-to-grave system boundary includes all five phases.

The assessment of life cycle GHG emissions of building materials, including concrete, followed three internationally recognized standards: PAS 2050 [4], WRI/WBCSD: The GHG Protocol [74] and ISO 14000 series [26]. According to these standards, both cradle-to-gate and cradle-to-grave can be used as system boundaries in the quantification procedure. As stated earlier, many LCA studies chose cradle-to-gate as system boundary due to the large number of uncertainties in the use and end-of-life phases (e.g. [3,75]). As a result, a significant number of labelling related studies used cradle-to-gate as system boundary (e.g. [9,5]). Table 1 presents these LCA studies using cradle-to-gate or similar as system boundaries to quantify the life cycle GHG emissions of concrete.

Take the Hong Kong Carbon Labelling Scheme (CLS) for example, it is a voluntary eco-labelling scheme launched by the Construction Industry Council (CIC) and administered by Zero Carbon Building Ltd. (ZCBL) in December 2013. It aims to provide verifiable and accurate information on the carbon footprint of construction materials for the communication between clients, designers, contractors and other end users [9]. The labelling scheme focuses on a single impact category: climate change. It covers cement and reinforcement bars at the time of the study with 30–50 types of construction materials to be labelled in the future.

As shown in Table 1, the assessment of carbon footprint of Portland cement under the Hong Kong CLS is based on a "cradle-to-site" approach. The cradle-to-site approach covers all GHG emissions and removals arising from raw materials acquisition through production, transportation of the product to the border of Hong Kong [9]. The selection of cradle-to-site as system boundary is based on the Product Category Rule (PCR) provided by Environmental Production Declaration (EPD) [15]. The PCR classifies the life cycle of cement into three stages, which are:

- *Upstream processes*: Upstream processes include extraction of raw materials and transportation of raw materials to manufacturing facilities.
- *Core processes*: Core processes include manufacturing of the final product, maintenance of machines, packaging and treatment of waste generated.
- *Downstream processes*: Downstream processes include transportation from manufacturing facilities to construction sites and reuse, recycling or recovery.

Downstream processes, including use and end-of-life phases, are optional in the PCR of the CLS. According to CIC [9], the GHG emissions and removals in the use stage of cement are insignificant and therefore neglected in the labelling scheme. In addition, the end-of-life phase is also excluded from the scheme based on the irreversible nature of cement products.

Similarly, other carbon labelling schemes e.g. the Singapore Green Labelling Scheme (Singapore) and the CarbonCounted (Canada) use cradle-to-gate as system boundary to assess and report the GHG emissions in the life cycle of cement and concrete. As can be seen from Table 1, other LCA studies of concrete also exclude the use and end-of-life phases and the most commonly used justifications to exclude these two phases include:

- The impact of use phase on the life cycle GHG emissions of concrete is minimal (e.g. [9,17]).
- The impact of end-of-life phase on the life cycle GHG emissions of concrete is minimal (e.g. [20]).
- There are many uncertainties in the use and end-of-life phases of concrete (e.g. [45,49,75]).

Table 1
LCA studies of concrete that do not use cradle-to-grave as the system boundary.

Studies	Content	Country	System boundary	Reasons
Athena Sustainable Materials Institute [1]	LCA of cement and concrete	Canada	Cradle-to-gate	The impact from use and end-of-life phases is minimal.
CIC [9]	LCA of Portland cement	Hong Kong	Cradle-to-site	The impact from use phase is insignificant; The irreversible nature of cement in the end-of-life phase.
Flower and Sanjayan [17]	LCA of concrete manufacture	Australia	Cradle-to-gate	The impact from use and end-of-life phases is minimal.
Habert et al. [20]	LCA of geopolymer based concrete	France	Cradle-to-gate	Geopolymer based concrete is similar to other concrete in the use phase; Concrete is inert in the end-of-life phase.
Nisbet et al. [45]	LCA of Portland cement and concrete	USA	Cradle-to-gate	Uncertainties in use and end-of-life phases.
O'Brien et al. [46]	LCA of concrete	Australia	Cradle-to-site	The aim of the study is to assess the environmental impacts in the production and transportation processes.
Oliver-Solà et al. [49]	LCA of concrete sidewalks	Spain	Cradle-to-grave excluding end-of-life phase	Concrete is durable; Many uncertainties in the end-of-life phase.
Prusinski et al. [53]	LCA of slag cement concrete	USA	Cradle-to-gate	The aim of the study is to assess the environmental impacts in the production process.
Sjunnesson [59]	LCA of concrete	Sweden	Cradle-to-grave excluding use phase	The impact from use phase is minimal.
Wu and Low [75]	LCA of precast concrete columns	Singapore	Cradle-to-gate	Long duration of use phase; Many uncertainties in the end-of-life phase.
Wu and Xu [77]	LCA of recycled aggregate concrete	China	Cradle-to-gate	The aim of the study is to assess the environmental impacts in the production process.

Table 2
Factors in the use phase of concrete that can affect its life cycle GHG emissions.

Studies	Content	Country	Factors affecting the life cycle GHG emissions of concrete		
			Carbonation	Maintenance activities	Other indirect emissions
Borjesson and Gustavsson [2]	LCA of concrete in building construction	Sweden			Significant
Chehovits and Galehouse [7]	LCA of concrete pavements	France		Significant	
Collins [8]	LCA of a built concrete bridge	Australia	Significant		
Kikuchi and Kuroda [31]	LCA of demolished and crushed concrete	Japan	Significant		
Kjellsen et al. [32]	LCA of concrete	Nordic countries	Significant		
Lippke et al. [36]	LCA of concrete house in cold and warm climate	USA			Significant
Loijos [37]	LCA of concrete pavement	USA	Significant	Can be significant	Significant
Mehta [38]	The potential to reduce the environmental impact of concrete	USA		Can be significant	
Nielsen [43]	LCA of concrete	Denmark			Can be significant
Ochsendorf et al. [48]	LCA of concrete building	USA		Significant	
Santero and Horvath [55]	LCA of concrete pavement	USA			Significant
Weiland and Muench [69]	LCA of Portland cement concrete interstate highway	USA		Significant	
Su et al. [62]	LCA of concrete and steel buildings	China			Significant

- The aim of the study is to assess the GHG emissions in the production process only [53,77].

However, none of these studies use sensitivity analysis to justify their decisions to exclude the use and end-of-life phases. Furthermore, recent studies found that using cradle-to-gate can be biased, leading to overestimation of GHG emissions (e.g. [34]) or underestimation of GHG emissions [7]. These may pose challenges to the credibility of these studies as recent studies show that use phase and end-of-life phases of concrete can have a significant impact on its life cycle GHG emissions (e.g. [51,8,48,37]).

3. Use phase of concrete

The impact of the use phase of concrete on its life cycle GHG emissions can take the form of carbonation, maintenance and rehabilitation and other indirect emissions. Carbonation is a process in which carbon dioxide that was emitted during cement production would rebind to $Ca(OH)_2$ in the cement. Depending on the compressive strength of the concrete and the average annual temperature, a 1.4% re-absorption to 15% re-absorption could be anticipated [55]. Maintenance and rehabilitation activities can increase the GHG level in terms of electricity or fuel consumption. In addition, other sources of indirect emissions can also be caused by thermal or non-thermal effects of concrete, e.g. thermal mass and surface roughness.

Table 2 summarizes the factors in the use phase of concrete that can affect its life cycle GHG emissions.

3.1. Carbonation

Many studies have validated the importance of carbonation to the life cycle GHG emissions of concrete. Collins [8] found that the life cycle of concrete should be divided into primary and secondary life. While primary life equals to the traditional life cycle from extraction of raw materials to demolition, secondary life commences when concrete is recycled and is utilized in new construction. The carbonation of the recycled concrete was negative 136.2 kg CO_2 equivalent, causing the life cycle GHG emissions of

concrete to reduce by 23.6%. The carbonation rate is dependent on a few characteristics of the concrete, such as porosity, water/cement (w/c) ratio and particle size. Porosity is usually represented by comprehensive strength. Low comprehensive strength normally indicates high porosity and therefore high carbonation rate [32]. The w/c ratio is also found to be very important. Concrete with high w/c ratio can have a carbonation rate that is ten times higher than the carbonation rate of the concrete with low w/c ratio [14]. Carbonation rate can also be affected by particle size. Concrete that has particles within the range of 1–8 mm has the highest carbonation rate [14]. The effect of carbonation on the life cycle GHG emissions of concrete varies. For example, Kikuchi and Kuroda [31] found that carbonation can help reduce approximately 5.5% of the life cycle GHG emissions of concrete. However, the 5.5% still far exceeds the 1% threshold proposed by PAS 2050 to exclude an emission source.

3.2. Maintenance, rehabilitation and other indirect emissions

As can be seen from Table 2, maintenance, rehabilitation and other indirect emissions in the use phase of concrete can have a significant impact on its life cycle GHG emissions. Major maintenance and rehabilitation should be conducted over the life cycle of concrete to maintain a satisfactory level of performance. This is especially important for frequently used concrete structures such as concrete pavements. Recent studies found that maintenance can have a higher impact on the life cycle GHG emissions of concrete than expected. For example, Loijos [37] argued that when maintenance is excluded from the life cycle assessment of concrete, analysis is needed to verify its appropriateness. In the case of a rural concrete road, the maintenance and rehabilitation accounts for 5.6% of the life cycle GHG emissions. The 5.6% far exceeds the 1% threshold proposed by PAS 2050 to exclude an emission source. Chehovits and Galehouse [7] also reported that major rehabilitation can take up to 16.8% of the GHG emissions emitted in the pre-use phases (i.e. from extraction of raw materials to construction). The magnitude of the effect of maintenance on the life cycle GHG emissions of concrete has neither been clearly established in previous LCA studies nor been generalized to all concrete products. Therefore, a large research gap emerges relating to the treatment of maintenance when calculating the life cycle GHG emissions of concrete.

Other sources of indirect emissions can also affect the life cycle GHG emissions of concrete. Concrete has a positive impact on energy consumptions of buildings due to its high thermal mass [43]. The magnitude of the effect also depends on the intended way to use concrete. For example, when used as pavements, concrete can increase fuel consumption of vehicles in terms of pavement roughness, an effect of wear accumulated on the road surface [37]. Pavement roughness can be caused by unevenness of the road and megatexture. Rough pavements with high vehicle traffic can cause high global warming potential. Rough pavements even obtain a higher rank of global warming potential than the extraction of raw materials which is normally considered as the highest impact on the life cycle GHG emissions of concrete [55]. In addition, traffic delay that occurs during maintenance and rehabilitation activities over the life cycle of concrete pavements results in significantly high GHG emissions due to the additional fuel consumed by vehicles during the delays [56]. Table 3 shows the GHG emissions from traffic delays caused by maintenance and rehabilitation on the life cycle of concrete pavements.

Table 3
GHG emission caused by traffic delay during concrete pavement maintenance and rehabilitation.

Pavement type	GHG emissions caused by traffic delay (metric tons CO_2e per km)	Life cycle GHG emissions (metric tons CO_2e per km)	Percentage
Interstate road	1930	6188	31.19
Freeway	1199	3981	30.12
Principal road	435	2361	18.42
Minor road	199	1289	15.44
Collector road	171	944	18.11
Local road	40	518	7.72

Adapted from Loijos [37].

In addition, when used as structural building material, concrete is believed to have relatively lower energy consumption than steel, leading to lower GHG emissions. Su et al. [62] found that the annual life-cycle energy consumption for heating, ventilation and air-conditioning (HVAC) in concrete-construction buildings is 12% less than in steel-construction buildings if similar occupant behaviour exists. The GHG emissions in the use phase of concrete-construction buildings is 14% less than those in the use phase of steel-construction buildings [62]. This saving will not be recognized in current carbon labelling schemes because these schemes use cradle-to-gate as system boundary for product labelling. Similarly, variability across locations, such as physico-chemical and ecological properties of the environment, background concentrations of chemicals and human population density, may also have a significant impact on the life cycle GHG emissions of concrete, although these factors are generally not taken into account in current LCA studies [24]. In a case study presented by Lippke et al. [36], forest sequestration, which could be determined by the number of hectares required to support the construction of one useful life cycle for the house, acted as an offset to the emissions of the concrete house. The life cycle GHG emissions of concrete were 31.8% lower when such offset was taken into consideration [36].

4. End-of-life phase

Although the post-use of materials is not covered in “cradle-to-gate” LCA studies, efficient management of post-use materials arising from the building sector has already been a priority issue in the many countries, such as European Union [16]. Landfilling, for example, as one of the strategies to process concrete at the end-of-life phase, can create high environmental impact [12]. The building construction sector in many countries therefore set up voluntary material recovery target to divert post-use materials from landfills. In Sweden, the building construction sector has aimed to divert about half of its post-use materials from landfill [63]. According to the Construction Materials Recycling Association [10], 140 million tons of concrete are recycled annually in the United States and the number has been increasing since 2010.

Many studies excluded the end-of-life phase in the GHG quantification process either because it has relatively low impact or there are too many uncertainties in the end-of-life phases. For example, [47] found that the impact of demolition process and debris transportation is relatively small compared to construction or use. Similarly, Junnila et al. [29] stated that end-of-life phase contributes minimally to the overall life-cycle energy use and emissions if the building is demolished and the demolished materials are transported to a landfill. These studies argued that the exclusion of end-of-life phase in the quantification process of the life cycle GHG emissions of concrete is appropriate if concrete is demolished and transported to landfill at the end of its life cycle. However, these studies did not take carbonation into account.

Once the concrete is crushed and stored at a landfill, a 75% re-absorption rate can be achieved because much more surface area becomes exposed to the atmosphere [44]. The carbonation process can reduce the GHG emissions emitted during the calcinations process.

Moreover, many recent studies have shown that the end-of-life phase can have a considerable impact on the level of GHG emissions of concrete if concrete is recycled and reused at the end of its life cycle. For example, Kjellsen et al. [32] found that approximately 75% of precast concrete products would carbonate within 5 years after demolition and this, combined with the carbonation in the use phase, can lead to a 25% reduction of CO_2 emitted in the calcinations process. Similarly, Pade and Guimaraes [51] argued that concrete demolition and recycling can have a large impact through the process of carbonation which is largely dependent on the recycling practices. In the case study of the concrete produced in Iceland, Pade and Guimaraes [51] found that 37% of concrete is carbonated after demolition because concrete is crushed and stockpiled for a period between 2 weeks and 4 months for carbonation before reuse. Dodoo et al. [12] also found that the carbonation of concrete is underestimated if the end-of-life phase is not taken into consideration and that the carbon emissions from fossil fuel used to recover the post-use concrete should not be overlooked. Thormark [65] stated that 37–42% of the embodied energy of building, which is defined as the total primary energy consumed over its life cycle, can be recovered by recycling. Based on the results of these studies, it can be concluded that the life cycle GHG emissions of concrete is significantly overestimated if concrete is demolished and reused as recycled concrete aggregate at the end of its life cycle. This is particularly true as concrete recycling is now a common end-of-life treatment for concrete and the percentage of recycled concrete has been rising these years. For example, according to Kelly [30], the recycling rate in the U.S. was about 50% in 1998 and the rate kept rising since 1998. Norway and Sweden expect that by the year 2010 approximately 70% of demolished concrete will be recycled [51].

Concrete reuse can further reduce its life cycle GHG emissions. According to World Business Council for Sustainable Development [71], the reuse of concrete blocks in their original form has less environmental impact although only a limited market currently exists. Lamond [35] discussed the process to remove and reuse hardened concrete. Although the study did not quantify the GHG emissions that could be reduced, the life cycle GHG emissions would be lower considering that a significant portion of concrete blocks were reused. Thormark [64] found that the energy consumption of a house in its life cycle could be reduced by 60% if concrete blocks and tiles were reused, thus reducing its life cycle GHG emissions.

The end-of-life treatments and their impact on the life cycle GHG emissions of concrete are shown in Table 4. Unlike the use phase of concrete, end-of-life treatments other than direct landfill, including crush and landfill, recycling and reuse, will normally reduce the life cycle GHG emissions. The impact magnitude of these end-of-life treatments is significant which justifies the necessity to include end-of-life treatments to calculate the life cycle GHG emissions of concrete.

5. GHG compensation through green building architect

The GHG emissions of concrete can be compensated through green building architect, such as the use of natural light, solar and wind energy for heating and cooling applications. The GHG compensation caused by these technological advancements should be considered when evaluating the life cycle GHG emissions of concrete. Some of the design strategies that can lead to GHG compensation include reducing loads, selecting ambient energy sources and using efficient equipment control strategies [67]. The green building technological advancements and their impact on the life cycle GHG emissions of concrete are shown in Table 5.

For example, heating loads can be reduced through the use of high performance building envelopes (insulation, windows and air tightness) combined with heat-recovery ventilation [67]. According to Harvey [22], the European Passive House Standard and advanced houses in Canada and the U.S. have achieved reductions in heating energy use by 75–90% compared with conventional practices. Similarly, external cooling loads can be reduced through the use of high-reflectivity building surfaces, external shading devices and other external insulation [21]. According to Hacker et al. [21], a mixed mode of cooling system combining the use of air conditioning and external shading and other passive designs can lead to a carbon reduction of 70%. The operational emissions savings will offset initial embodied carbon emissions of all building materials in 11–25 years. Gratia and De Herde [18] and Voss et al. [68] also found that passive cooling and ventilation methods can significantly reduce the energy requirements of the building, thus reducing greenhouse gases. It seems that the GHG compensation through heating and cooling load reduction should be considered when evaluating the life cycle GHG emissions of concrete in office buildings.

Solar energy can also be utilized effectively in green buildings to reduce the energy required for heating purposes. The reduction can be achieved by orienting glazing for optimal solar gain and balancing glazing area [40]. The energy saving by using passive solar systems for space heating and cooling is significant when used in combination with conventional systems for heating,

Table 4
End of life treatments and their impact on the life cycle GHG emissions of concrete.

Studies	Content	Country	End-of-life treatment	Impact
Dodoo et al. [12]	LCA of concrete building	Sweden	Crushed; 90% is used as recycled aggregate	Significant
Junnila et al. [29]	LCA of office buildings	Europe and USA	Demolished and landfill	Minimal
Kjellsen et al. [32]	LCA of precast concrete products	Nordic countries	Crushed; Processed as recycled aggregate	Significant
Nielsen and Glavind [44]	Green concrete	Denmark	Crushed and landfill	Significant
Ochoa et al. [47]	LCA of concrete building	USA	Landfill	Minimal
Pade and Guimaraes [51]	LCA of ready mixed concrete	Nordic countries	Crushed Long stockpiling period	Significant
Thormark [64]	Reuse of concrete	Sweden	Reuse in original form and recycling	Significant
Thormark [65]	LCA of building	Sweden	Recycling	Significant
World Business Council for Sustainable Development [71]	Recycling of concrete	Not country specific	Reuse in original form	Can be significant

Table 5
The impact of GHG compensation through green building architect.

Studies	Country	Green building architect			
		Reducing heating loads	Passive cooling	Passive solar heating and cooling	Green roof
Harvey [22]	European countries	Significant			
Jenkins et al. [28]	UK	Significant			
Hacker et al. [21]	UK		Significant		
Gratia and De Herde [18]	Belgium		Significant		
Voss et al. [68]	German		Significant		
Harvey [23]	Not available			Significant	
Monahan and Powell [39]	UK			Significant	
Radhi [54]	Bahrain			Significant	
Wong et al. [70]	Singapore				Significant
Muga et al. [41]	USA				Significant
Niachou et al. [42]	Greece				Insignificant on well-insulated roofs

cooling, ventilation and lighting [50]. It can achieve a 30–50% saving in the primary energy use for heating and cooling in buildings [23]. The annual CO_2 emissions for houses in UK with passive solar design can be reduced by 47% when compared to average household emissions [39]. Similarly, Radhi [54] found that passive solar systems, along with other strategies in the energy efficiency code, can lead to a 25% reduction in energy consumption for office building in Bahrain and consequently a 7.1% reduction in carbon emissions.

Green roof is also an emerging technology in green building architect to reduce GHG emissions. Muga et al. [41] found that the life cycle GHG emissions of traditional built-up roofs are three times higher than green roofs. It should however be noted that the impact of green roof on the life cycle GHG emissions of concrete should be examined on a case-by-case basis. For example, Niachou et al. [42] found that although green roof has been proven to be effective in reducing annual energy consumption of office buildings by 1–15%, it has a minor effect on well-insulated roofs. The review shows that the technological advancements in green building may have a significant impact on the life cycle GHG emissions of buildings through GHG compensation. However, the research target of these technological advancements is building. There is a large research gap to systematically allocate the GHG compensation to the life cycle GHG emissions of building materials to evaluate their life cycle environmental performance. In addition, although various technological advancements are now adopted in green buildings, there is a lack of published international standards, national guidelines and industry guidelines to include these advancements and model the allocation of the GHG compensation to building materials.

6. A new GHG quantification standard: ISO 14067

The carbon labelling schemes of products followed PAS 2050, ISO 14000 series and WRI/WBCSD: The GHG Protocol. Although PAS2050 and the GHG Protocol have similar standards and are unlikely to result in significant differences in measurement outcomes, the industry needs one uniform and globally recognized standard for assessing and communicating GHG results at a practical level. ISO 14067: Carbon footprint of products – requirements and guidelines for quantification and communication was published in May 2013. It brings significant changes to current carbon labelling schemes in terms of allowing transparent communication of GHG results and can be used as the uniform standard for assessing and communicating GHG results. While there are many similarities among the three internationally recognized GHG standards, ISO 14067 clarifies and details the assessment method by providing some specific requirements on the selection of system boundary and simulating use and end-of-life phases.

The standard was proposed in the first ISO/TC (Technical Committee) 207/WG (Working Group) 2 meeting in April 2008. It was developed by over 100 experts from more than 30 countries, including developing countries such as China, Argentina, and Indonesia, and received a large number of comments from international involvement. According to ISO (2009), the first draft of ISO 14067 received 578 comments on Part 1: Quantification and 184 comments on Part 2: Communication. However, due to the objection raised by some countries, ISO 14067 was published as a Technical Specification rather than an internationally recognized standard in May 2013. The Technical Specification will be reviewed by May 2016 to determine whether it will be revised, withdrawn or published as an international standard.

ISO 14067 specifies principles, requirements and guidelines for the quantification and communication of the carbon footprint of products (CFPs), covering both goods and services, based on GHG emissions and removals over the life cycle of a product [27]. The impact of ISO 14067 on the use and end-of-life phases includes:

1. *Justifications for exclusions*: ISO 14067 proposes a process of refining the system boundary through sensitivity analysis. If life cycle stages are excluded from the CFP study due to their relatively low importance, sensitivity analysis should be conducted to validate and support the decisions and the results of the sensitivity analysis should be documented in the CFP report.
2. *Guidance on the simulation of use and end-of-life phases*: ISO 14067 offers step-by-step guidance to determine the use stage, the use profile (i.e. the assumptions underlying the assessment of emissions from the use stage) and the end-of-life phase. The guidance can be summarized into a three step process, which is:
   - *Step 1*: Aim for verifiable service life information that represents the actual usage pattern.
   - *Step 2*: Use simulations to model the use profile based on published technical information, such as published international standards, national guidelines, industry guidelines and documented usage patterns in the selected market (in order of preference), if step 1 cannot be completed.
   - *Step 3*: Use simulations to model the use profile based on the manufacture's recommendation for proper use, if step 2 cannot be completed.
3. *CFP label*: One important change in ISO 14067 is related to the use of CFP label to communicate cradle-to-gate CFP and partial CFP (i.e. emissions and removals from a restricted number of

isolated stages). Cradle-to-gate can be used as the system boundary of CFP study only if [27]:

- information on specific stages (e.g. the use and end-of-life stages of the product) is not available and reasonable scenarios cannot be modelled; or
- there are stages that are insignificant for the GHG emissions and removals of the product.

The use of cradle-to-gate may be justified for some building materials if the use and end-of-life phases of these materials do not contribute significantly to the life cycle GHG emissions. For concrete, however, as identified earlier, both use and end-of-life phases have a significant impact on its life cycle GHG emissions. Following the ISO 14067 guideline, their impact can be appropriately simulated through Building Information Modelling (BIM) or other simulation technologies.

The publication of ISO14067 is timely as it sets up standards relating to the selection of system boundary and limits the use of cradle-to-gate as the system boundary when the ecolabel information is intended to be publicly available. Previous assessment principles from PAS 2050, ISO 14000 series and WRI/WBCSD: The GHG Protocol provide flexibility for organizations and countries to develop their own assessment guidelines. However, such flexibility can limit the applicability of the standards and the credibility of the environmental information. Koning et al. [33] provided an example showing how increasing the discretion of choosing system boundaries in LCA studies can result in misleading results. Manufacturers can manipulate data in the operational stage to create “low carbon” products. ISO 14067 therefore helps to effectively prevent these situations and can lead to genuine results.

Fig. 1 summarizes the procedures to include use and end-of-life phases of concrete in the quantification procedure of its life cycle GHG emissions following the recommendations of ISO 14067. In the use phase, the exclusions of factors, such as carbonation, maintenance and rehabilitation and the intended way to use concrete, must be based on sensitivity analysis if the eco-label information is intended to be publicly available. Similarly, the exclusion of end-of-life treatments must be based on the result of sensitivity analysis demonstrating that end-of-life treatments generate less than 1% of the life cycle GHG emissions of concrete.

7. Simulation technologies

ISO 14067 provides opportunities for the building and construction industry to evolve in the aspect of addressing global climate change. Manufacturers and contractors are not allowed to use cradle-to-gate as the system boundary when the operational and end-of-life phases of the materials/products have a significant impact or can be well established or simulated. Simulations of operational and end-of-life phases have been conducted for a variety of building materials/products, such as concrete and steel. The proposition of using cradle-to-grave in ISO 14067 will promote the use of Building Information Modelling (BIM) or other simulation technologies to identify the GHG emissions of the materials/products in their true life cycle.

For example, GaBi (developed by PE-International) is a life cycle assessment tool which can be used to simulate the life cycle of products. One specific feature of GaBi is that it incorporates improved scenario analysis and enables life cycle comparisons. Both country specific and global average databases (e.g. Inventory of Carbon and Energy developed by UK) can be used in GaBi. According to Loijos [37], one of the primary benefits of GaBi is that the modelling of production and operation processes (i.e. the inputs and outputs in the life cycle of the products) can be parameterized. For example, the comprehensive strength and the w/c ratio of concrete can be a set of variables in GaBi. Changing the variables will lead to different designs and therefore different scenarios in GaBi. Using parameterized variables can help to understand the impact of these variables on the life cycle GHG emissions of concrete. In addition, GaBi provides a sensitivity analysis tool to quantify the impact. The provision of the sensitivity analysis tool is in accordance with ISO 14067 which mandates the use of sensitivity analysis to justify the decision to exclude certain life cycle stages.

The BIM software (e.g. Revit) allows engineers and designers to build a three-dimensional virtual model of a structure using parametric objects [60]. The databases in BIM can be exported to other platforms for specific analysis purposes, e.g. carbon audits in GaBi. The BIM plug-ins, e.g. the Integrated Environmental Solutions' Virtual Environment Revit Plug-in, are very useful to conduct full-process LCA while monitoring the effect of these changes to the building.

The Waste Reduction Model (WARM), developed by the Environment Protect Agency (EPA) can also be used to simulate the life cycle of concrete. However, unlike GaBi which monitors the whole life cycle of concrete, WARM focuses on end-of-life treatments, including recycling and landfilling. While landfilling includes collection of concrete and transport to landfill, recycling includes removal and crushing of concrete as well as other recycling practices. The simulation relies on two pre-defined scenarios: closed-loop allocation where no changes occur in the inherent properties of the recycled material and open-loop allocation where the material undergoes a change to its inherent properties [27]. Table 6 provides some simulation technologies that can be used to simulate the whole life cycle or isolated life cycle stages of materials/products.

8. Conclusions

The aim of GHG quantification is to provide useful, credible and transparent information for customers to make informed decisions. However, the flexibility given in previous LCA approaches, which results in the frequent use of cradle-to-gate at system boundary, limits the credibility of the environmental information. A review of previous studies on the life cycle assessment of concrete is presented to reveal how the use and end-of-life phases affect its life cycle GHG emissions. It is concluded that the use phase of concrete can have a significant impact on its life cycle GHG emissions in terms of carbonation, maintenance, rehabilitation and thermal or non-thermal effects. Similarly, end-of-life treatments other than direct landfill can also have a significant impact in terms of carbonation, recycling and reusing activities. Thus, using cradle-to-gate as system boundary to calculate the life cycle GHG emissions of concrete can be biased, leading to overestimation or underestimation.

The ISO 14067 restricts the use of system boundaries other than cradle-to-grave if the use and end-of-life phases of the products can be simulated. Sensitivity analysis must be provided to justify the decision to exclude use and end-of-life phases if these two phases are believed to have a minimal impact. The proposition of using cradle-to-grave in ISO 14067 will also promote the use of Building Information Modelling (BIM) or other simulation technologies, many of which have been well established in the building and construction industry, to identify carbon footprint in the products' true life cycle. With the support of these simulation technologies, the contribution of use and end-of-life phases to the life cycle GHG emissions of concrete should be included in future studies.

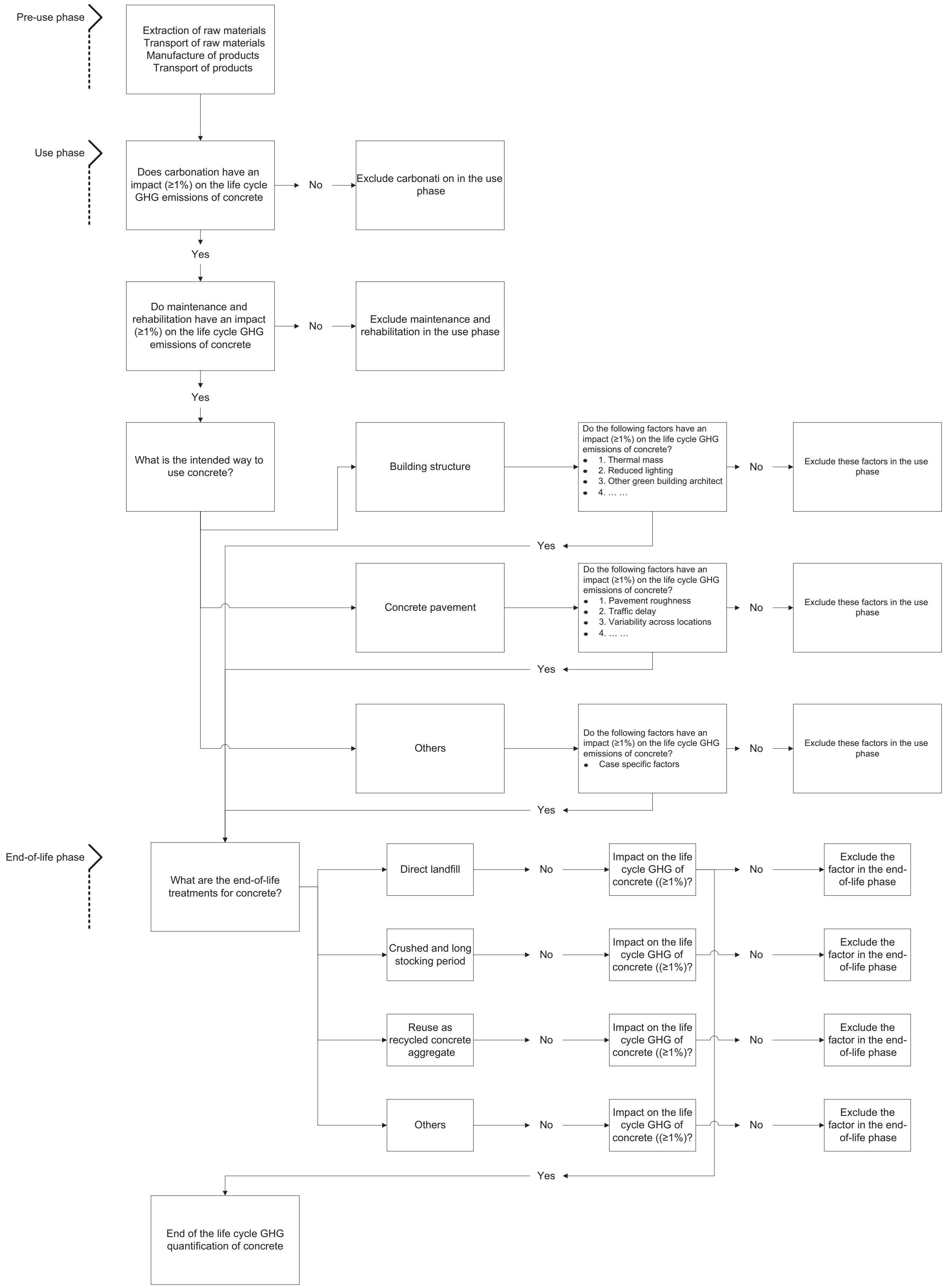

Fig. 1. An integrated procedure to include use and end-of-life phases of concrete in the quantification process of its life cycle GHG emissions.

Table 6
Simulation technologies in the life cycle assessment of building materials.

Simulation technologies	Functions	Examples
Building Environmental Performance Analysis System (BEPAS)	Quantification of the life cycle GHG emissions of buildings	Zhang et al. [78]
Building Information Modelling (BIM), e.g. Revit	3D virtual model of a building using parametric objects	Stadel et al. [60]
e-CALC	Quantification of the emissions of construction equipment	Sinhabuddin and Ariaratnam [58]
Economic Input–Output (EIO) – LCA	Quantification of the life cycle GHG emissions of materials/products	Guggemos and Horvath [19]
GaBi	Quantification of the life cycle GHG emissions of materials/products	Loijos [37]
SimaPro 7	Quantification of the life cycle GHG emissions of materials/products	Cass and Mukherjee [6]
WARM	Quantification of GHG emissions in the end-of-life phase	Donalson et al. [13]

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